# The Coherent Combination of Fibre Lasers - Towards Realistic Applications

Peter Tudor[a)], Laura Corner and Roman Walczak

*John Adams Institute, University of Oxford, Keble Road, Oxford, OX1 3RH, UK*

[a)]Corresponding Author: peter.tudor@physics.ox.ac.uk

**Abstract.** To drive a laser plasma wakefield, high peak-power laser pulses are required. For useful accelerator applications it is also necessary to have driving lasers with high efficiency, repetition rates and average powers. The coherent combination of Ytterbium doped fibre laser amplifiers is a promising potential solution and previous work has demonstrated the successful combination of near-identical ultrafast fibre lasers [1, 2, 3]. We report here the combination of significantly mismatched Ytterbium doped photonic crystal fibre amplifiers with a combination efficiency of 96% while the locked power output remained stable for 6 hours. The combined output of the system had a total gain of 12dB with no detrimental effect on the compressed pulse width observed.

## INTRODUCTION

Fibre lasers are attractive candidates to drive laser plasma wakefields as they possess high wall plug efficiencies, (typically two orders of magnitude larger than typical the Ti:Sapphire laser systems used for high peak power pulses) and high average powers. However, in order to drive a wakefield, high peak powers (typically TW) are required. Previous theoretical work [3] has shown that the maximum peak power which can be extracted from a photonic crystal fibre (PCF) is of the order of $\sim$ 10GW. So to drive a wakefield, the output of many fibres need to be combined together. A facility-scale coherently-combined fibre-laser system utilising potentially hundreds of PCFs will generate significant cost. These costs are likely to increase if stringent constraints on fibres being near-identical for efficient combination are necessary.

One aspect of designing a facility sized system is to identify where costs can be reduced by informed design choices. This includes identifying where tolerances can be relaxed which could potentially reduce the cost of individual components. The tolerances we refer to here are those of the PCFs themselves, testing the limits of the requirement for identical fibres for successful combination by combining non-identical PCFs. Here we demonstrate the successful coherent combination of two amplified PCFs in a Mach-Zehnder interferometer [4] stabilised using the Hänsch-Couillaud method [5]. The seed for the amplification and combination exeriment was a 6.49MHz pulsed Yb-doped fibre laser at 1032nm, with a stretched pulse duration of $\sim$ 250ps and a compressed pulse duration of $\sim$ 430fs. The output of this laser is then split equally at a polarising beam cube and each beam is then used to seed a PCF. The PCFs are themsleves significantly different, having different lengths (520mm and 820mm), different core sizes (70$\mu$m and 85$\mu$m) and internal structures. In addition, the 70$\mu$m core PCF contains polarisation maintaining stress rods while the 85$\mu$m core PCF does not. The subsequent effect of using different core sizes and the presence of protective end caps on one of the PCFs means that the wavefronts from each PCF are very different at the point of combination.

## Coherent combination of mismatched Photonic Crystal Fibres

The experimental setup is shown schematically in fig. 1.

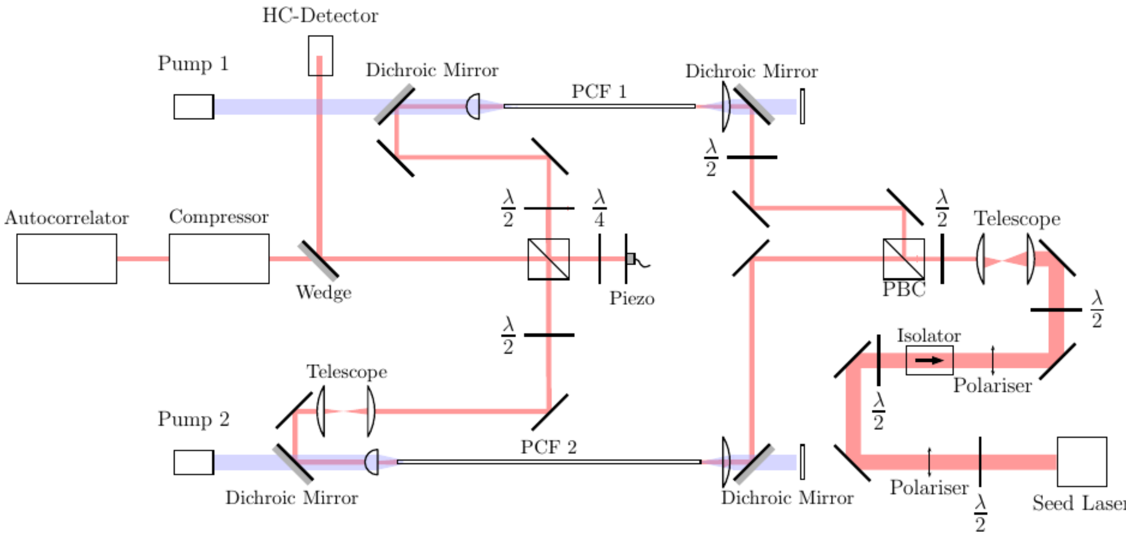


**FIGURE 1.** Experimental setup of two mismatched PCF amplifiers. Blue beams are pump lasers, red is the seed.

A Mach-Zehnder interferometer is used to combine the mismatched PCFs together, stabilised with a piezo-mounted mirror whose longitudinal position can be locked using the Hänsch-Couillaud method. Simple 1D pulse propagation simulations show that the difference in material dispersion between the two PCFs has little impact on the phase difference between the two pulses and still allowed for good combination. Indeed, a paramater space scan presented in theoretical work [6] of length of dispersive material against B integral for different bandwidths shows the estimated the figure of merit of combination. Here they came to the same conclusion. This is in part due to the relatively narrow 5.5nm (FWHM) bandwidth of the seed making it less sensitive to dispersive effects than a broader bandwidth pulse. The biggest obstacle to efficient beam combination are the differences between the wavefronts. The core size and beam path to the point of combination are different for each PCF so resulted in each beam having a different beam size and divergence at the combination beam cube. This translates into each beam haing a different radii of curvature when they combine, see fig 2. Simulations were performed on two beams with perfect spherical wavefronts but with different radii of curvature, combining to give interference rings.

The combination of these two beams from an experimental setup with no modification, as viewed through a polarising beam cube, can be seen in fig. 3a. Note the similarity to the simulations in fig. 2. This shows that the polarisation state of our unmodified combined beam varies radially outwards which is problematic for polarisation sensitive comonents such as the grating compressor. The combined beam should have a spatially homongeneous linear polarisation to avoid significant power loss in the compressor, this requires the two beams to be combined to be both matched in beam size and divergence at the point of combination. Placing a telescope in the 85$\mu$m PCF's beam line produced significantly better matching of the beam properties. Here, each lens's approximate-position in the beam line, their focal length and separation from each other is calculated via a MATLAB simulation. This resulted in the combined beam from fig. 3a being improved to that as seen in fig. 3d. The beam profiles of the 70$\mu$m and 85$\mu$m PCFs are seen in fig. 3b and fig. 3c respectively. It should also be noted that the combined beam profile is much cleaner, being more uniform than fig. 3b and less elliptical than fig. 3c.

The locked system is characterised as having a combination efficiency of 96% with an average output power of 4.86W. The combining efficiency is defined as [7]:

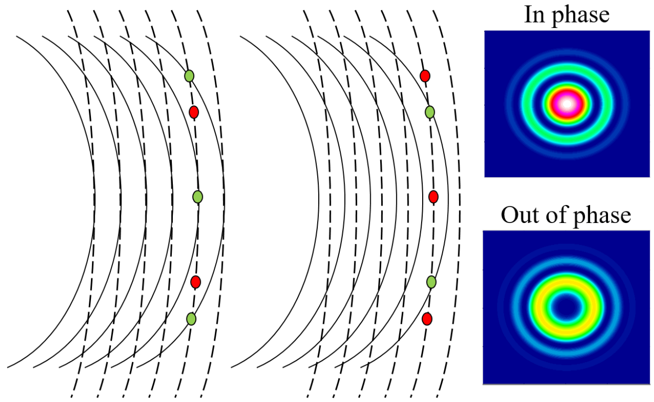


**FIGURE 2.** The beam profiles right show the simulation results of two perfectly spherical wavefronts with different radii of curvature combining to produce a beam with a polarisation state varying radially outwards. To the left is a 2D representation of the interaction of these wavefronts for illustration. Here the solid line is a wavefront which is horizontally polarised whilst the dashed line is a wavefront which is vertically polarised. The coloured spots are places where the polarisation state is well defined as linear with the red and green representing orthogonal polarisation states with respect to each other. Everywhere in between the red and green spots (following the dashed line) are varying degrees of elliptical polarisation. When the beams are displaced temporally the beams shift from in phase to out of phase. This is observed as the interference rings growing or shrinking in size towards the centre.

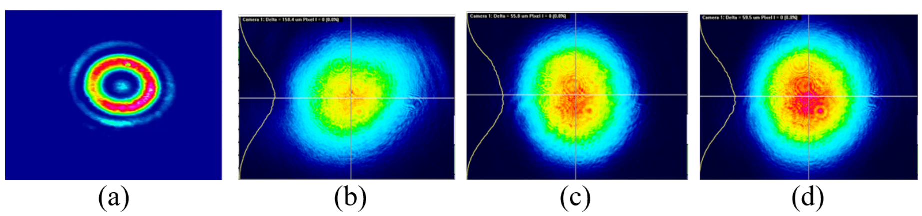


**FIGURE 3.** These figures show the beam profile as viewed through a polarising beam cube after the output of the system. A half wave plate is used to change the polarisation state of the incident beam into the beam cube. This is due to the 70$\mu$m and 85$\mu$m PCF beam profiles having orthogonal polarisation states. (a) The combined beam of the 70$\mu$m and 85$\mu$m PCFs with mismatched wavefronts. (b) 70$\mu$m beam profile. (c) 85$\mu$m beam profile. (d) Combined beam profile.

$$\eta_{comb} = \frac{P_{comb}}{\sum_i P_i} \tag{1}$$

Where $\eta_{comb}$ is the combining efficiency, $P_{comb}$ is the locked combined output power of the system and $P_i$ are the individual (unlocked) powers measured after the point of combination. However, for two channels, the system efficiency is a better metric for characterising the system, which is defined as per (1) except that the individual powers are measured immediately prior to the point of combination. This then accounts for the power losses due to imperfect combining elements and polarisation losses. Here, the system efficiency is measured to be 86%. Fig. 4 shows the autocorrelation of the combined amplified beam overlaid with the seed beam. The compressor is initially tuned for the seed laser and then readjusted for the amplified beam. Only minor adjustment is required and the amplified pulse compression is as good as the best unamplifed pulse compression.

The pulse energy from this system, given the average output power and a repetition rate of 6.49MHz, is calculated to be $\sim$ 747nJ before compression. Calculating the central pulse (assuming a Gaussian profile) to contain 75% of the pulse energy, the compressed pulse gives a theoretical peak power of 1MW before compressor efficiencies are accounted for. This system is running at a total gain of 12dB, with the 70$\mu$m and

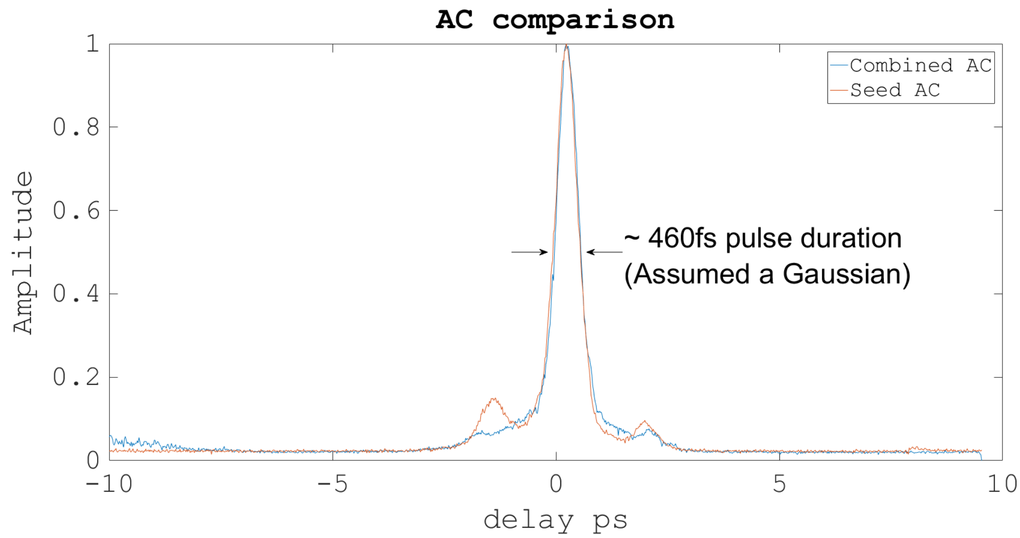


**FIGURE 4.** This shows the autocorrelations of the seed and amplified beam overlaid.

85$\mu$m PCFs having gains of 11.6dB and 12.4dB respectively. The degree of linear polarisation of the system output was characterised to be 83%. These results make up a low power test of the setup, higher power tests are planned in the near future. In these we expect to be able to reach higher peak powers.

## Conclusion and outlook

This is the first time, to the best of our knowledge, that two significantly different PCF amplifiers have been successfully coherently combined. The system had a total output power 4.86W which gives a theortical peak power of 1MW before compressor efficiencies. The system was characterised as having a gain of 12dB, a system efficiency of 86%, a degree of linear polarisation of 83% and the locked power output was stable over the course of 6 hours. It is clear from the setup that it would be unwise to purposefully choose to have amplifiers with such different properties. However, this experiment shows that a coherent-combination setup is able to withstand significant mismatch between the amplifiers with a high degree of linear polarisation. In terms of its effect on an industrial scale system, from a manufacturer's perspective, this translates to reduced PCF tolerances in terms of length and core size. Whereas before one could expect tolerances of $\pm\sim 0.5$mm and $\pm\sim 1\mu$m respectively (for example), the tolerances could possibly be relaxed to $\pm\sim 5$mm and $\pm\sim 2\mu$m respectively or even further in terms of length. This would contribute towards a reduced wasteage and cost per fibre which could have a significant impact on the total cost of a combined system consisting of hundreds of fibres. The next steps to be taken from here are to increase the average output powers of each PCF in the current configuration and then to increase the peak power by reducing the repetition rate of the system.

## REFERENCES


[1] L. Daniault, M. Hanna, L. Lombard, Y. Zaouter, E. Mottay, D. Goular, P. Bourdon, F. Druon, and P. Georges, Opt. Lett. **36**, 621–623Mar (2011).

[2] E. Seise, A. Klenke, J. Limpert, and A. Tünnermann, Opt. Express **18**, 27827–27835Dec (2010).

[3] A. Klenke, S. Hädrich, T. Eidam, J. Rothhardt, M. Kienel, S. Demmler, T. Gottschall, J. Limpert, and A. Tünnermann, Opt. Lett. **39**, 6875–6878Dec (2014).

[4] D. N. Schimpf, J. Limpert, and A. Tünnermann, J. Opt. Soc. Am. B **27**, 2051–2060Oct (2010).

[5] T. Hansch and B. Couillaud, Optics Communications **35**, 441 – 444 (1980).

[6] A. Klenke, E. Seise, J. Limpert, and A. Tünnermann, Opt. Express **19**, 25379–25387Dec (2011).

[7] J. Limpert, *CLEO: 2014*, CLEO: 2014 p. SW3E.3 (2014).